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International Climate Regime beyond 2012

Are Quota Allocation Rules Robust to Uncertainty?

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Abstract

Bringing the United States and major developing countries to control their greenhouse gas emissions will be the key challenge for the international climate regime beyond the Kyoto Protocol. But in the current quantity-based coordination, large uncertainties surrounding future emissions and future abatement opportunities make the costs of any commitment very difficult to assess *ex ante*, hence a strong risk that the negotiation will be stalled.

Lecocq and Crassous use a partial equilibrium model of the international allowance market to quantify the economic consequences of the main post-Kyoto quota allocation rules proposed in the literature and to assess how robust these consequences are to uncertainty on future population, economic, and emissions growth. They confirm that, regardless of the rule selected, the prices of allowances and the net costs of climate mitigation for all parties are very sensitive to uncertainty, and in some scenarios very large. This constitutes a strong barrier against adopting any of these schemes if no additional mechanism is introduced to limit the uncertainty on costs.

On the other hand, parties' preferred (least-cost) rules are essentially robust to uncertainty. And although these preferences differ across countries, the authors' analysis suggest some bargaining is possible if developing countries make a commitment and join the allowance market earlier in exchange for tighter quotas in the North. This underscores the importance of the rules governing the entry of new parties into the coordination. But the magnitude of the win-win potential strongly depends on how different abatement costs are assumed to be between industrial and developing countries, and on how long that gap is assumed to persist.

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International climate regime beyond 2012
Are quota allocation rules robust to uncertainty?

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1. Introduction

Under the Kyoto Protocol, OECD countries and economies in transition, the so-called Annex B countries, have accepted binding greenhouse gases (GHG) emission targets for period 2008-2012, or first commitment period. Developing countries have no such commitment, but may host emission reduction projects through the Clean Development Mechanism (CDM).

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Though consistent with the "*common but differentiated responsibilities*" principle of the 1992 UN Framework Convention on Climate Change (UNFCCC), this partial coordination remains largely an "*unfinished business*" (Jacoby *et al.*, 1999). In fact, Annex B countries minus the United States (which has decided not to ratify the Kyoto Protocol) represent only a third of current World emissions[1]. In other words, to meet the UNFCCC's objective to "*stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*", participation of the United States and of major emitters among developing countries is required. This is the main challenge of the post-2012 international climate mitigation regime.

There are strong reasons to believe that this regime could replicate the current cap-and-trade approach. In fact, the majority of the early GHG mitigation policies, such as the trading schemes in Denmark and the UK or the intra-firm trading within Shell and BP are based on that model (Rosenzweig *et al.*, 2002). In addition, some provisions of the Kyoto Protocol such as the possibility of banking allowances already assume a second commitment period. The now likely[2] entry into force of the Protocol will also result in the creation of specific institutions such as national registry systems or market clearinghouses. Combined with the traditional inertia of the diplomatic process, all these elements create strong incentives to perpetuate current *status quo*. In the present paper, we assume cap-and-trade is replicated.

As pointed out by Weitzman (1974), in a quantity-based coordination, all the uncertainty falls on costs. In the climate mitigation case, this difficulty is magnified: business-as-usual scenarios and future abatement costs are by definition unobservable, and margin of errors are potentially very large. There is thus a strong risk that the negotiation be stalled as no Party wishes to commit to such uncertain agreement (Hourcade, 1994). This hypothesis is unfortunately confirmed by the vagaries of the Kyoto Protocol, where uncertainties on costs have fueled the United States and other Nations' deep skepticism (Nordhaus, 1998, Victor, 2001, Hourcade and Ghersi, 2002).

The present paper aims at assessing the extent to which future negotiations might face the same difficulty, by quantifying the impact of uncertainty on the distributional outcome of the various quota allocation rules proposed to guide the distribution of allowances beyond 2012. That will provide us with some insights on how Parties, in particular developing countries, might rank rules in the incoming negotiations on future commitments (2005).

To do so, we first survey the main quota allocation rules that have been proposed in the literature (Section 2). Second, we develop a partial equilibrium model of the allowance market, which aims at simulating the economic consequences of the adopted rules (Section 3), under a wide range of assumptions about population, economic and emission growth in the baseline scenario described in section 4. After having ensured all the quota allocation rules yielded the same cumulative emission level in the long run (section 5), we successively analyze how baseline impact on quota distribution (section 6), price of allowances (7) and regional costs and benefits of the climate policy (8). The last section concludes by discussing the implications of these results for the design of the international regime beyond 2012.

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[1] Fossil-fuel CO_2 only. Coverage would reach 56% with the USA (IEA, 2001). Even if the emissions of current Annex B plus the USA were curbed down to zero in 2010, concentrations would still be on the rise beyond 2100 in most business-as-usual scenarios because of emissions from developing countries.

[2] To enter into force, the Kyoto Protocol must be ratified by 55% of the Parties, accounting for more than 55% of the 1990 emissions of Annex B. The former condition is already met, but the latter requires Russia and either Canada or Poland to ratify. Russia and Canada have declared they would ratify at the Johannesburg summit, but neither has done so as of Nov.30, 2002.

2. A survey of main quota allocation rules

Several schemes – commonly referred to as "quota allocation rules" – have been proposed to guide a quantity based regime beyond 2012. They define both principles for the allocation of quotas to Parties and, perhaps more importantly, a timetable for developing countries to take on binding target[3].

These proposals are usually designed to apply not only to the second (2013-2017), but also to subsequent commitment periods. This is a rather good proxy for the negotiations to come (negotiations on the second commitment period are scheduled for 2005), as Parties, developing countries in particular, have expressed strong desire for visibility on these periods before they take on any firm commitment[4].

Some of these schemes are ready-to-implement, while others just outline grand principles, leaving operational details unresolved. To ensure consistency in the modeling exercises we describe all the rules through the template represented in Figure 1 below. We denote "observable parameters" all the measurable parameters, which be used or computing quotas. Though the list is virtually infinite, an international agreement can realistically be based only on those of these parameters on the value of which there is enough confidence is almost all countries so that endless controversies can be avoided. Only a handful of parameters such as population, GDP or GHG emissions thus qualify[5].

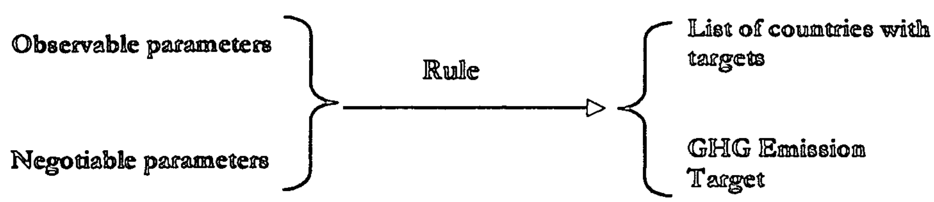

Figure 1: Generic structure of quota allocation rules

By "negotiable parameters", we denote the normative parameters which enter as input to the formula computing quota, and on which Parties would have to negotiate and agree on. Examples of negotiable parameters include GDP *per capita* thresholds below which Parties do not have to have a constraint on their emissions, weights of attached to different parameters in a multi-criteria allocation rules or year at which a certain goal (e.g. *per capita* allocation of quotas) has to be achieved.

We now present the main quota allocation rules suggested in the literature, starting somewhat arbitrarily from the simplest schemes (in terms of volume of observable parameters required) to the most complex. Section 2.1 presents the grandfathering schemes, section 2.2 the polar *per capita* allocation and 2.3 the various schemes that have been proposed to combine the two approaches. We then review approaches based on other parameters such as ability to pay (2.4), opportunity to abate (2.5) and

[3] To the authors' knowledge, all proposals for a quantity-based coordination beyond Kyoto assume that the Parties would allocate allowances among themselves freely. Auctioning these rights does not seem to be discussed.

[4] China and the G77 have warned that "*there would be no agreement on carbon trading until the question of emissions rights and entitlements is addressed equitably*" (UNFCCC document SB/1998/MISC.1/Add.3/Rev.1).

[5] Some international sharing agreements are based on more complex parameters, for example the Country Policy and Institutional Assessment evaluation for IDA allocation. But this is feasible only when one group of Party (here the lenders) has the final authority on the value of these parameters.

responsibility in historic emissions (2.6). We last discuss the so-called "bottom-up" approaches where national quotas are built by aggregation of sectoral targets (2.7).

2.1. Grandfathering (flatrate)

In this scheme, allowances are distributed *pro rata* past emission levels. This is the most common approach in international sharing agreements over scarce resources, which reflects widespread acceptance of the legal doctrine of prior appropriation (Sterner, 2002). Examples include the milk quotas within the European Union (Burton, 1985), most Individual Tradable Quotas for fisheries (Sterner, 2002, p.382-383) and, to some degree at least, the US SO_2 trading program (Joskow *et al.*, 1999). In the climate change affairs, the 1992 non-binding target to curve 2000 GHG emissions down to 1990 levels (UNFCCC, 1992) reflected this logic that was, to a certain extent, followed at Kyoto since the three major groups of emitters in Annex B (US, EU and Japan) have similar absolute targets compared to 1990 emissions (-6%, -8% and –7% respectively). We will consider here a simple flat rate architecture.

In this scheme, the policy parameters are a reference year and a rate of emission reduction compared to that reference for each commitment period. The only negotiable parameters are the volumes of GHG emissions at the reference year. The formula itself is very simple, with c indexing countries, and t indexing successive commitment periods.

Quota(c,t) = Reference year emissions (c) * Reduction rate (t) (1)

To control the timing of entry of developing countries, we introduce trigger mechanism based on *per capita* GDP. As soon as the country GDP exceeds a given threshold, it is given an emission quota. Otherwise, it has no constraint on its GHG emissions.

2.2. Immediate per capita allocation (Agarwal and Narain's proposal)

In a resounding 1991 paper, Anil Agarwal and Sunita Narain proposed an immediate *per capita* allocation of GHG emission rights, which they presented as the only equitable way of allocating emission quotas among countries. It is beyond the scope of this paper to discuss the normative foundations of this claim (see e.g. Godard, 2000 for a review), but we must note that *per capita* allocation appeals to many participants of the climate policy debate (e.g. Baer *et al.*, 2000, Blanchard *et al.*, 2000).

In this scheme, the only negotiable parameter is a *per capita* emission quota for each period. Last measured population level is the observable, with the following simple formula:

Quota(c,t) = Population (c,t-1) * *Per capita* emission quota (t) (2)

Since current *per capita* emissions across countries are very different (see Table 1 below), this formula might generate large quantities of so-called hot air, "windfall credits" or quotas in excess from baseline scenarios in developing countries. To safeguard the environmental integrity of the trading mechanism, some restrictions on the trade of hot air might be introduced. The variants with progressive rather than immediate *per capita* allocation are discussed separately below.

2.3. Transitions from grandfathering to *per capita*

Although *per capita* allocation has strong normative appeal, an immediate application of this scheme is often regarded as unrealistic in terms of political acceptability and economic feasibility. As Table 1 indicates, *per capita* emissions today are indeed very unequal among countries. To solve this dilemma, progressive approaches have been proposed whereby quotas are first allocated based on past emissions, and then gradually based on population[6].

Numerous transition schemes have been proposed (e.g. Manne and Richels, 1997, French proposal to the AGBM[7], 1996). Key parameters are the date at which convergence is effective, and the form of the transition. We choose to illustrate this group with the contraction and convergence proposal of the Global Common Institute (Meyer, 2000), in which total allowed emissions and sharing principles are clearly separated. In this scheme, a total authorized emission level is set for each commitment period. Shares of that quota are then computed as follows:

Party	*Per capita* (tC/cap)
United States*	5.48
European Union*	2.31
China	0.63
Russia*	2.63
Japan*	2.43
India	0.25
Canada*	4.30
Korea	2.17
Ukraine*	1.95
Mexico	1.02
South Africa	2.33
Poland	2.26
Australia*	4.52
Brazil	0.49
Saudi Arabia	3.56
Islamic Rep. of Iran	1.14
Indonesia	0.28
North Korea	2.35
Taiwan	2.45
Turkey	0.79
World average	1.06

Table 1: 1998 Per capita fossil-fuel CO_2 emissions for top 20 emitters (source: IEA, 2001).

[6] Interestingly, transition towards *per capita* allocation appears in the recent Marrakesh Accords (2001), in a draft decision /CP7 titled *Principles, nature and scope of the mechanisms pursuant to Articles 6, 12 and 17 of the Kyoto Protocol.* Sixth preambula in this decision reads "*Emphasizing that the Parties included in Annex I shall implement domestic action [...] with a view to reducing emissions in a manner conducive to narrowing per capita differences between developed and developing country Parties while working towards achievement of the ultimate objective of the Convention*". Although we understand this statement does not preclude the choice Parties will make when they have to negotiate actual allocations by 2005, it demonstrates the widespread interest that transitions towards *per capita* allocation commands.

[7] The first Conference of the Parties to the UNFCCC created the *Ad Hoc* Group on the Berlin Mandate (AGBM) in 1995 to discuss quota allocation in the future Kyoto Protocol.

$$\text{Quota(c,t)} = \text{World Quota(t)} * \left[\left(\frac{\text{Pop(c,t-1)}}{\text{World Pop(c,t-1)}} - \frac{\text{Quota(c,t-1)}}{\text{World Quota(t-1)}}\right) e^{-\alpha(\text{Convergence Year} - t)} + \frac{\text{Quota(c,t-1)}}{\text{World Quota(c,t-1)}}\right] \quad (3)$$

(Quota(c,t-1) is replaced by Emissions(c,t-1) in the first period)

The initial shares are thus based on previous period emissions. But as time goes by, the weight attached to the share of population increases. When the convergence year is reached, shares of the quota are uniquely based on relative populations, as in the *per capita* approach.

Negotiable parameters include world emission quota at each period, a reference year for historical emissions, a convergence year and a speed of convergence represented by parameter α. The higher this parameter, the slower the convergence. Observable parameters include population and reference year GHG emissions. No transition scheme is proposed since the rule is by itself a transition. Potential variants include others convergence formula (e.g. linear transition). As the immediate *per capita* approach, contraction and convergence may generate "windfall credits', especially in the medium and long run when quota allocation become strongly dependent on population.

2.4. Ability to pay (Proposal by Jacoby, Schlamensee and Wing)

A large body of literature argues for allocating quotas in function of the ability to pay. Various proposals by Parties prior to Kyoto already made that argument (e.g. submissions by Poland, 1997, Estonia, 1996, Russia, 1995 or South Korea, 1997 to the *Ad hoc* Group of the Berlin Mandate[7]). The proposal by Henry Jacoby *et al.* (1999) is an operational scheme based on the same principle.

In this proposal, countries take on emission targets when they cross a predefined *per capita* GDP threshold. At first, their emissions are capped but still allowed to grow, but the richer they get, the tighter the constraint becomes up to a point where the country is effectively required to reduce its emissions from one period to the next. Technically, this rule is as follows:

$$\text{If GDP(c,t-1)} < \text{GDP}^*\text{, then no quota} \quad (4)$$

$$\text{If GDP(c,t-1)} \geq \text{GDP}^*\text{, then Quota(c,t)} = \text{Quota(c,t-1)} * \left[\gamma - \alpha\,(\text{GDP(c,t-1)} - \text{GDP}^*)^{\beta}\right]$$

(Quota(c,t-1) is replaced by Emissions(c,t-1) for Parties entering) (5)

Negotiable parameters include the *per capita* GDP ceiling below which countries are exempted (parameter GDP^*), the initial allowed emission growth rate (γ), and the short term (α) and long term (β) reduction rates. Observable parameters include *per capita* GDP at previous period and, for Parties taking commitment for the first time, GHG Emissions at previous period. We assume that Parties within Kyoto would enter with their Kyoto targets.

2.5. Multicriteria (Norwegian proposal)

Some Parties have proposed to base emission quotas on a wider range of parameters consisting of ability to pay (captured by *per capita* GDP), opportunity to abate (represented by carbon intensity of GDP) and *per capita* emissions (submissions by Norway, 1996, Australia, 1997, Iceland, 1997 to the AGBM[7]). Since these proposals did not fully specify the weights of each of these parameters, they are better described as families of rules. We focus here on the Norwegian proposal, which has been extensively analyzed in the literature on post-Kyoto allocations (Reiner and Jacoby, 1997, Ringius *et al.*, 1998).

In this proposal, quotas are allocated based on the following recursive formula (6), where the ratio between each parameter and the average for all regions with quotas is used as indicator, and where a, b and c are positive weights. Under these specifications, one may expect to see the rate at which quotas decrease rise abruptly when developing regions join in and make the averages drop. From that point onward indeed, the reference on the basis of which the emission quota varies is lower. However, we will see in the simulations that this effect has very limited impact.

$$\text{Quota}(c,t) = \text{Quota}(c,t\text{-}1) * \left[1 - a\,\frac{\text{GDP}(c,t\text{-}1)/\text{POP}(c,t\text{-}1)}{\text{Average GDP/POP}(t\text{-}1)} - b\,\frac{\text{Emissions}(c,t\text{-}1)/\text{GDP}(c,t\text{-}1)}{\text{Average Emissions/GDP}(t\text{-}1)} - c\,\frac{\text{Emissions}(c,t\text{-}1)/\text{POP}(c,t\text{-}1)}{\text{Average Emissions/POP}(t\text{-}1)} \right] \quad (6)$$

Negotiable parameters are the weights a, b and c of each parameter. Observables include GDP, population and emissions at previous periods. For Parties currently within Annex B, we can assume that initial quota would be their Kyoto quota. For developing countries, the initial quota would be their emissions at time of entry into force (or last measured emissions). As in the flatrate and Jacoby case, we introduce a *per capita* emission ceiling to govern developing countries' entry in the system.

2.6. Historical responsibilities (Brazilian proposal)

The Government of Brazil has proposed to index quota allocation on the relative responsibility of each countries in current temperature increase has been widely studied and reviewed (UNFCCC, 1997, Den Elzen *et al.*, 1999). In this scheme, as in the Contraction and Convergence approach, a global target is set. This global quota is then shared depending on each Party's contribution to current temperature increase, which is computed based on historical GHG emissions time series, and on a climate model linking GHG emissions and mean surface temperature increase. As such, proponents of this scheme argue, it is consistent with the polluter-pay principle. The original proposal also includes a Clean Development Fund that would collect fines imposed on Parties with excess emissions, and would fund emission reduction projects in the developing world. But the same methodology can be extended to the whole world, developing countries included (Den Elzen *et al.*, 1999).

In the Brazilian proposal, prime policy parameters are a world emission target, a model representing the impact of GHG emissions on mean surface temperature, and an initial year for counting historic GHG emissions. As underscored by Den Elzen *et al.*, the agreement on these policy parameters might not be easy to obtain: the nature of the greenhouse gases included in the analysis, as well as the whether or not CO_2 emissions from sinks are included have strong impact on the final result. Moreover, there are several competing models to represent the atmospheric carbon cycle and temperature response (McAvaney *et al.*, 2001).

Negotiable parameters include present and historic GHG emissions. Although emission time series are only reconstructions based on other indicators (fuel consumption, economic growth, etc.), and thus largely uncertain, Den Elzen *et al.* suggest that uncertainties on pre-1950 data does not matter too much for the final sharing, because of the low level of these emissions, and the progressive "decay" of GHG in the atmosphere. Den Elzen have also suggested to include a threshold above which developing countries would take on commitments.

2.7. Bottom-up Approaches

All the proposals we have discussed so far proceed from a top-down logic: quotas are computed based on global indicators such as national population, GDP or national emissions. However, this approach only captures cross-country variations in the structure of the economies to the extent they are reflected in aggregate indicators. This is why bottom-up approaches have been proposed.

In the Triptych proposal (Phylipsen *et al.*, 1998 for Annex B only, extended to the whole world by Groenenberg *et al.*, 2000), the economy of each country is divided into three sectors: heavy industry, power generation and domestic. Abatement targets for the former two derive from assumptions about growth, technical change and technical substitution. Quotas for the third sector are based on a *per capita* emission allocation. The Triptych approach was used in particular to guide the intra-EU sharing of the Union's global -8% target under the Kyoto Protocol.

The Multi-Sector Convergence Proposal (Jansen *et al.*, 2001) distinguishes 7 sectors: power production, households, transportation, industry, services, agriculture and waste. For each of these sectors, assumptions about growth and technical change are made, on the basis of which sectoral quotas are computed. The authors also propose to grant supplemental emission allowances indexed on parameters such as climate, population density, agriculture type, and the transitional situation of some economies or renewable energy potentials.

In both proposals, the set of observable parameters is rather large. GHG emissions must be disaggregated in a rather thin way. Similarly, basic economic indicators (growth rate, output level, etc.) must be known for each of the considered sectors. Negotiable parameters include growth assumptions for each sector, as well as benchmarks for estimating abatement potential. Although the Triptych approach was used in practice within the EU, it is not clear whether this experiment could be replicated with a larger, and more heterogeneous set of countries, given the important data requirement of this scheme

3. Assessing distributive impacts of allocation rules with international allowance trading

To assess the distributive impacts of each of these quota allocation rules for all Parties, we develop a partial equilibrium model of the allowance market.

3.1. The model

Let the world be divided into regions indexed by r. For each 5-year commitment period from the first (2008-2012) to the ninth (2048-2052), indexed by t, the quota allocation rule defines a subset R(t) of regions with commitments, and a set of quotas Q(r,t) for all regions r in R(t). As discussed above, the formula for quota derivation depends on the allocation rule being considered, with generic function:

$$Q(r,t) = f(Q(r,t-1), \text{Observables}(t-1), \ldots, \text{Observables}(1), \text{Observables}(\text{before } 2008)) \quad (7)$$

We assume a perfect market for emission allowances to which participate all regions within R(t). All regions out of R(t) are excluded from the market. During period t, each region can thus purchase a quantity Ep(r,t) on that market (Ep is negative is the region is net seller). As a result, and assuming both full compliance and no banking or borrowing across periods, the constraint each region faces is given by (8) below, where E(r,t) is the net GHG emissions of that region during commitment period t:

$$E(r,t) \leq Q(r,t) + Ep(r,t) \tag{8}$$

Let a(r,t) be the domestic abatement level, expressed in percentage of business-as-usual GHG emissions Eb(r,t). By definition:

$$E(r,t) = [1\text{-}a(r,t)]\ Eb(r,t) \tag{9}$$

We assume that the marginal costs of GHG emissions abatement C_{rt} in region r at period t depend only on the relative abatement level a(r,t). We also assume that each region is price-taker on the allowance market. Let p(t) be the equilibrium price on that market at period t. Each region thus minimizes its budget constraint under program:

$$\mathrm{Min}_{a(r,t)} \int_0^{a(r,t)} C_{rt}(\alpha)d\alpha + p(t)\ Ep(r,t) \tag{10}$$

And individual compliance constraint:

$$[1\text{-}a(r,t)]\ Eb(r,t) \leq Q(r,t) + Ep(r,t) \tag{11}$$

The set of optimal regional abatement $a^{\circ}(r,t)$ solution to problem (10-11) is given by the equalization of individual marginal abatement costs, which also yields the equilibrium market price of allowances:

$$C_{it}(a^{\circ}(i,t)) = C_{jt}(a^{\circ}(j,t)) = p(t) \tag{12}$$

3.2. Discussion of key assumptions behind this model

The above framework incorporates four important assumptions that are worth explaining:

The allowance market is strictly limited to regions with emission quota. Under the Kyoto Protocol, the Clean Development Mechanism (CDM) allows Annex B Parties to finance emission reduction projects out of Annex B and claim the resulting emission reductions against their targets. In practice however, long project preparation time and the necessity to strictly verify that the proposed projects indeed reduce GHG emissions compared to what would have happened otherwise suggest that the potential supply of credits from the CDM might remain small compared to obligations of Annex B Parties, at least for the first commitment period (Josko and Michaelowa, 2002). In the current paper, we do not consider the CDM or CDM-like mechanisms.

A perfect allowance trading market. We assume that all Parties are price-takers and do not model the possibility that few Parties might use their (supply or demand) market power to their advantage. This is a rather restrictive assumption as long as most of the supply of allowances is controlled by a limited number of Parties such as Russia and Ukraine in the first commitment period (Ellerman *et al.*, 1998). Second, Parties are assumed totally free to trade their allowances. Again this is an approximation, because of the so-called supplementarity condition of the Kyoto Protocol, which states that trading shall be "*supplemental to*" domestic policies and measures. But no quantified cap and trade is introduced[8].

[8] The Marrakesh Accords state that any point of time no Party shall hold less than 70% of its baseline emissions in its national account.

Full compliance at each period of time, no borrowing or banking. The political economy of non-compliance is beyond the scope of the present paper. In this analysis, we simply aim at showing what are the consequences of full compliance, and at identifying when and where tensions, if any, occur. In fact, even assuming full compliance, the Kyoto Protocol provides for banking of emission allowances between periods (borrowing is formally forbidden, although the compliance regime is akin to[9]). We do not capture this mechanism and will come back to it when we discuss the evolution of prices in section 7.

Parties do not inflate their emissions before joining: Rules which base first quota on past baseline emissions (most particularly Jacoby, Multicriteria and Flatrate) create perverse incentives for countries either to inflate their emission statistics or to postpone environmentally friendly investments, policies and measures. This risk is in fact constitutive of all schemes where quotas are somehow based on an environmental indicator (emissions, carbon content of GDP, share of renewables in power production, etc.). The measurement issue can probably be solved or contained. The magnitude of the incentive to delay climate friendly policies, on the other hand, is unclear. We know that so far major policies affecting GHG emissions have been taken "in passing" (Hourcade *et al.*, 1996) for reasons totally unrelated to environment. But we also know that this was largely due to ignorance of the climate externality. Attitudes might change if a clear financial reward, in the form of potential carbon sales, is attached to the decisions leading to highest emissions. For the present exercise, we simply assume that the Parties do not behave strategically vis-à-vis future quotas. We will come back to this point in conclusion.

4. Calibration and representation of uncertainty

4.1. Business-as-usual scenarios

We divide the world into 12 regions (Table 2). In a database of long-term scenarios assembled by the Intergovernmental Panel on Climate Change (IPCC) (Morita and Lee, 1998), we selected all the scenarios which (a) provided projections for population, GDP and CO_2 emissions[10], (b) at least up to 2050 and (c) with worldwide scope but disaggregated in at least 5 regions.

[9] In fact, the compliance provisions of the Kyoto Protocol – to be ratified separately by Parties – state that Parties with emissions in excess of their allowances at the end of the first commitment period will have to redeem that excess volume plus a 30% penalty during the next commitment period. Borrowing is thus taxed and not strictly forbidden (Hourcade and Ghersi, 2002). But it would make sense for a Party to use that provision only if it assumed during the next period the price of carbon would be much lower, or that its domestic abatement costs would suddenly decrease. Such configurations, we will see, can occur.

[10] From this point onward, we restrict our analysis to fossil-fuel CO_2 emissions because there is limited regionalized information on business-as-usual emissions and on abatement costs for both non-fossil-fuel CO_2 emissions (deforestation) and non-CO_2 GHG (such as methane and nitrous oxide).

Annex B		Non annex B	
Region	Description	Region	Description
USA	USA	CPA	Centrally Planned Asia (incl. China)
CANZ	Canada, Australia and New Zealand	SAS	South Asia (incl. India)
WEU	Western Europe	ROA	Rest of Asia
EEU	Eastern Europe	MENA	Middle East and North Africa
FSU	Former Soviet Union	SAFR	Sub-Saharan Africa
JPN	Japan	LAM	Latin and Central America

Table 2: World Regions in our model.

Out of the 416 scenarios in the database, 19 meet these criteria: the 6 IPCC IS92 scenarios (Leggett *et al.*, 1992), the 7 EPA scenarios (Morita and Lee, 1998) and the 6 IIASA-WEC 1995 scenarios (Nakićenović *et al.*, 1998). We also include the IPCC 1998 scenarios (Nakićenović and Swart, 2000), which constitute the most comprehensive and most recent scenarisation exercise undertaken by the IPCC. Annex I describes how the data has been disaggregated or reaggregated to fit into the 12 selected world regions, and how 1990 and 2000 data have been harmonized.

These scenarios, with the exception of the IS92 family, are "computerized storytelling": they translate numerically a set of predefined assumptions (storylines) using computable general equilibrium models to achieve some degree of internal consistency. The IS92 scenarios juxtapose assumptions on population, economic and emissions growth (Pepper *et al.*, 1998). We include them because they serve as reference in a large number of publications.

The 6 IS92 scenarios are articulated around median IS92a (0.97% average annual population growth rate between 2000 and 2050, 2.52% economic growth rate and 1.21% emissions growth rate). IS92b to f are variants. IS92b assumes slightly lower emissions due to increased environmental awareness. IS92c is characterized by low population and low economic growth rate. IS92d is a variant of 92c with higher economic growth rate. IS92e represents another extreme with high economic growth and high emission growth. Last, IS92f explores very high population growth.

The IPCC *Special Report on Emissions Scenarios* (SRES, Nakićenović and Swart, 2000) describe four families of scenarios characterized by high/low openness of the regional economies and high/low awareness of (non-climate) environmental issues. We use the representation of these scenarios computed with the IMAGE model (Alcamo *et al.*, 1998). Family A1 (high openness, low awareness of environment) is characterized by a rapid stabilization of World population (2050), very high growth (+3.81% annual average) and high technical change. Three variants represent three possible technology directions: intensive fossil-fuel (A1f), rapid penetration of non-renewable energies (A1t) and median (A1b). B1 (high openness, high awareness of environment) is characterized by slightly slower growth (+3.21%), but lower emissions overall due to rapid diffusion of non-carbon technologies.

A2 (low openness, low awareness of environment) represents the polar case: a regionalized world with lower growth and high population. Coal is dominant in many regions because of low extraction costs. Technical change and energy efficiency are limited. Last, family B2 (low openness, high awareness of environment) represents sustainable development in a regionalized world. Emissions are lowest overall, but population is higher than in A1 and A2, and economic growth lower.

The 7 EPA1998 scenarios were built during the preparation of the SRES. Around median EPA1, they explore higher/lower openness of the economy, and thus higher/lower economic growth rate and higher/lower assumptions about technical change. EPA2 is high/high, EPA3 high/low, EPA4 low/high and EPA5 low/low. EPA6 and 7 are variations around EPA1 assuming higher (respectively lower) economic growth and technical change in the OECD.

The IIASA-WEC scenarios all assume the same population baseline (1% average annual growth rate). They differ by the economic growth rate, and by the structure of primary energy supply. Scenarios A1, A2 and A3 all assume fairly high economic growth rate (+2.6%) and high energy efficiency gains (0.9% annually). A1 relies mostly on coal on gas, assumed abundant, A2 represents a coal based future and A3, on the other hand, assumes high reliance on nuclear and on renewables, with progressive phasing out of fossil-fuels. B is somehow a median scenario with lower economic growth, and balanced development of renewables vis-à-vis fossils. Last, C1 and C2 assume rapid phase out of fossil fuel. They yield the lowest emission levels overall, and differ only by the extent to which nuclear is used.

Scenario	Population variation 2000-2050 (%)	*Per Capital* GDP variation (%)	Carbon intensity of GDP variation (%)
EPA1	0.91	1.4	-1.1
EPA2	0.74	2.3	-1.5
EPA3	0.91	1.47	-0.75
EPA4	0.91	1.47	-1.30
EPA5	1.13	0.7	-0.7
EPA6	0.91	1.9	-1.4
EPA7	0.91	1.0	-0.7
A1b	0.71	3.1	-2.0
A1f	0.71	3.1	-1.7
A1t	0.71	3.1	-2.4
A2	1.21	1.0	-0.8
B1	0.71	2.5	-2.5
B2	0.86	1.9	-1.9
IS92a	0.97	1.55	-1.31
IS92b	0.97	1.55	-1.41
IS92c	0.51	0.9	-1.5
IS92d	0.51	1.8	-1.9
IS92e	0.97	2.2	-1.4
IS92f	1.34	1.3	-1.2
IA1	1.00	1.6	-1.7
IA2	1.00	1.6	-1.2
IA3	1.00	1.6	-2.0
IB	1.00	1.1	-1.3
IC1	1.00	1.1	-2.5
IC2	1.00	1.1	-2.5

Table 3: Kaya decomposition of 2000-2050 emissions growth in the 25 selected scenarios.

We use the so-called Kaya decomposition to explore the relative impact of population growth, economic growth and carbon content of the economy on overall emissions growth[11] (Table 3). First, we see that a majority of the scenarios have population growth assumptions in the range of 0.9% to 1.0%.

Economic growth and carbon content of the economy, on the other hand, are more dispersed, as shown on Figure 2 below. We can distinguish four main groups: high growth, high decarbonization scenarios on the lower right side (A1b,f and t and B1), low growth, high decarbonization scenarios on the lower left (IC1 and IC2), low growth, low decarbonization scenarios on the upper right (EPA5,7 and A2) and a central cluster which explores – at similar population growth rate (except for EPA2, IS92c, d and f) variations around a "central point" of +1.5% growth rate and –1.5% decarbonization.

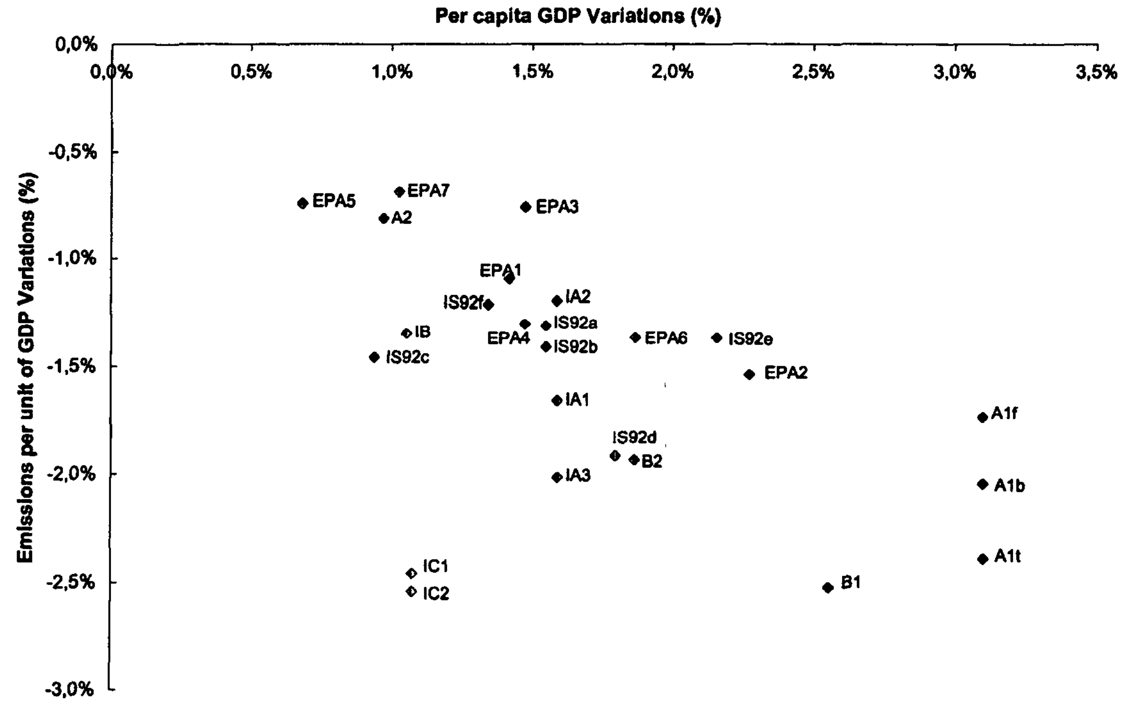

Figure 2: Evolution of World Gross Product and carbon intensity of value added 2000-2050 (annual average) for selected scenarios

The same figure drawn for developing countries only would show higher economic growth rate assumptions (up to +6.1% in the A1 scenarios). It would also show a clearer linear relation between the variations of *per capita* GDP and the variations of carbon intensity of GDP. The fact that this relation be better respected in developing countries can be discussed, but this is beyond the scope of the present paper.

[11] Variations in carbon intensity of GDP result from changes in the structure of the economy, i.e. in the primary energy content of each dollar of value added, and of modifications in the structure of the energy system, i.e. the carbon intensity of energy.

Let us last note that according to a comprehensive review of long-term economic and emission scenarios undertaken by the IPCC, the set we have selected gives a good representation of the range of all the plausible images of the World at 2050 that have been proposed in the literature (Nakićenović and Swart, 2000). This is illustrated on Figure 3 below shows the world population, GDP and emissions trajectories in the 25 scenarios retained in this study, compared with the range of all the scenarios in the SRES database in 2050 (red bar). The only exception is for emissions, where a few projections are IS98A1f.

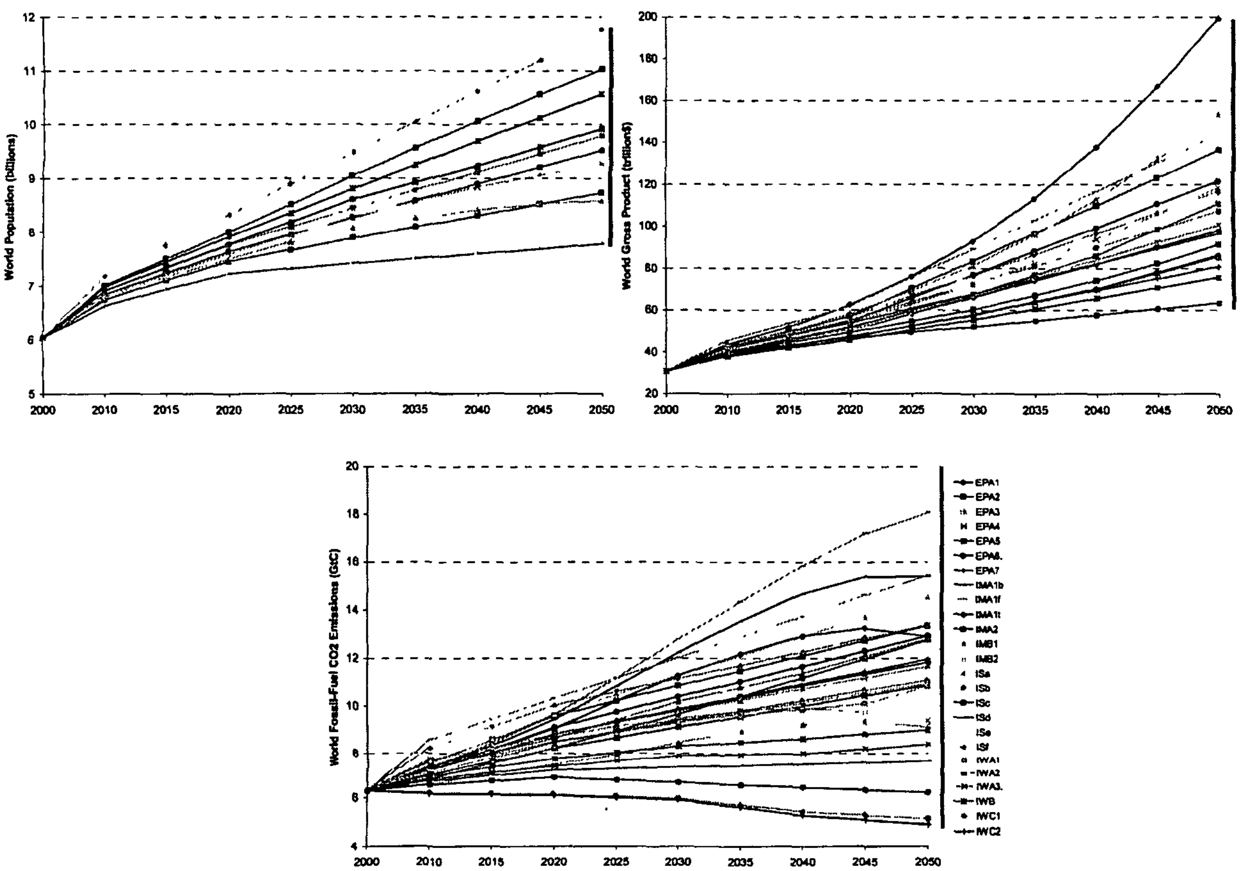

Figure 3: Evolution of world population, gross product and fossil fuel CO_2 emissions 2000-2050 in selected scenarios.

4.2. Marginal abatement costs

For the first commitment period, we use a set of regional marginal abatement costs curves (MACCs) produced by Ellerman *et al.* (1998). We simply rescale the original functions to make them depend on the percentage of abatement (as opposed to volume of abatement), and adapt them at the margin to fit our geographical coverage (see Annex 1 for details). These MACCs are quadratic, with regional coefficients are provided in Table 4 below.

$$C_{\pi}(a) = \alpha a^2 + \beta a \qquad (13)$$

These MACCs were computed with EPPA, a computable general equilibrium model of the World's economy (Ellerman *et al.*, 1998). They thus provide for each region an aggregated representation of the macroeconomic costs of imposing a given constraint on CO_2 emissions, during the first commitment period. On top of direct technical costs of reducing GHG emissions, they also capture cross-sectoral and cross-country spillovers (e.g. through modifications in the prices of energy, modifications of the balance between carbon intensive and non-carbon intensive goods, or impacts of carbon flows on the trade balance.

Region	α	β
USA	1689.11	73.53
CANZ	2786.52	769.99
JPN	2717.01	159.61
WEU	1893.65	-46.72
EEU	1232.59	19.36
FSU	1338.98	3.06
CPA	224.79	43.01
SAS	354.29	38.40
ROA	445.86	116.12
MENA	2749.84	280.89
LAM	594.35	43.09
AFR	594.35	43.09

Table 4: Regional marginal abatement cost curve functions coefficients.

According to a review of economic analysis of the Kyoto Protocol conducted by Weyant (1999), the EPPA MACCs are in the middle of the range of 10 models tested for the USA and Europe. For Japan, the model produces higher than average costs (although by far not the highest), and for CANZ, EPPA estimates are on the lower side at low emission reduction levels, and on the higher side for high emission reduction levels (pp.xxiii-xl). For developing countries, fewer comparison points are available, but comparisons with results from the Second Generation Model (Fischer Vanden *et al.*, 1993) suggest that EPPA MACCs are similar.

EPPA MACCs are *a priori* linked to the business-as-usual scenario, which is integrated in the EPPA model. To use them with all the baseline scenarios we have selected, we make the assumption that from one scenario to the other, the distribution of abatement opportunities by cost is roughly similar, but that the volumes of each class of abatement varies depending on the size of overall emissions (which is captured by writing the MACC as a function of percentage of abatement instead of pure volume). We will come back to this widely made assumption in the next phase of our research.

Beyond 2012, and in the absence of an in-house top down or bottom up model on which to base costs estimates, we simply "extend" the MACCs to the nine commitment periods. To do so, we start from the classification of abatement opportunities proposed by Jaccard *et al.* (1997). They distinguish three main categories:

- Energy demand management (e.g. through taxes, fiscal incentives, information campaigns, etc.), and changes in end-use equipment (e.g. energy efficiency of appliances): decisions are typically made by private decision-makers (households, or decentralized levels in companies). The turnover of capital stock ranges from a few years to two decades.
- Modifications of infrastructure equipment and industrial processes: this encompasses buildings efficiency, major transit modes, and industrial and power-producing infrastructure, the turnover of which is measured in decades. Centralized public and/or private decision-makers largely govern this level. Every decision involves an amount of capital whose order of magnitude is far higher than in previous level.
- Land-use and urban planning: this level is driven both by infrastructure decisions and by specific public policies. These policies can either be explicit, i.e. aimed at shaping urban forms or the distribution of the human settlements, or implicit, i.e. influencing land use and urban patterns through subsidies to mobility, or rules governing tenants and landlords relationships.

We first make the assumption that each period brings new abatement opportunities of the first category ("short term"), in a volume essentially independent from previous period abatement decisions. Indeed, if we discard induced effects of incentives on preferences and behavior, demand-side management is essentially reversible: if payments are not renewed from one period to the next, final consumers revert back to previous consumption patterns. Similarly end-use equipment are on average replaced from one period to the next, hence providing – leaving aside the effect of previous period abatement on technology and consumer preferences – a whole new set of abatement opportunities.

Since we reason at a very aggregated level, both geographically and over time, and at the margin of a baseline scenario, where a given level of goods and services is assumed to be delivered regardless of abatement decisions, we can consider that the set of abatement opportunities from the second category ("long term") at each point of time is independent from previous abatement decisions (Arrow, 1999). However, this assumption is valid only if abatement lèvels remain low enough not to trigger premature replacement of existing capital stock: otherwise, the set of abatement opportunities at next period would be altered (see Lecocq *et al.*, 1998 for an explicit representation of capital stock vintages). We will come back to this point when we discuss the abatement trajectories we obtain.

The question is now to determine the volume and prices of this new set of abatement opportunities. We will make here the assumption that the relative distribution of low-cost, high cost abatement opportunities remains unchanged from one period to the next. This is a disputable assumption, which does not capture the fact that the contribution of each sector to emissions might vary from one period to the next, and thus change the relative distribution of cheap and expensive abatement opportunities.

Because of technical change, lower costs for clean technologies should result in a downward translation of the MACC. But as clean technologies penetrate the market, some previously available abatement opportunities disappear as they are now integrated in the business-as-usual scenario, and the MACC is translated leftwards. The net effect on the MACC is not clear.

An additional complication comes from induced technical change, which covers cumulative effects such as learning-by-doing, network externalities, etc. This is potentially a very important factor for long-term climate policies, but the way these effects should be represented and the calibration of the models is still very controversial (Hourcade and Shukla, 2001, p.550). Consequently, we choose here not to try and use these specifications for clarity sake.

On this basis, and assuming that the two effects of autonomous technical change cancel out, we "extend" our MACCs to future periods by assuming they remain identical over time. We thus use the coefficients of Table 4 for all commitment periods. This is consistent with findings from Le Pesant (1997), who estimated MACCs for future commitment periods based on simulation results from the Second Generation Model (Fisher-Vanden *et al.*, 1993) and found that the same curve could approximate with good confidence the model's response to a constraint on emissions at various periods. We will come back on MACCs for future period in a subsequent research.

5. Parametrization of quota allocation rules

Before estimating the economic consequences of the adoption of quota allocation rules, we have to calibrate the different rules. For the time being, we focus only on the first five rules described in section 2, namely Flatrate, immediate *per capita* allocation, Contraction and Convergence, Jacoby and Multicriteria. We will introduce the Brazilian proposal and possibly bottom-up approaches, depending on data availability, in the next step of this research.

For all the rules we test, we assume that the Kyoto Protocol enters into force without the US for the first commitment period. The selected rule applies for the second and all subsequent periods. The rules are as described in section 2, and we make three additional assumptions:

- For Contraction and Convergence and Per Capita, all regions, developed and developing alike, take commitments as soon as in 2013.
- For the other three rules, a per capita GDP threshold governs the entry of Parties. That feature was an integral part of the Jacoby rule, and we also apply it to Flatrate and Multicriteria. This threshold applies to all regions, meaning that if Parties currently within Annex B have a *per capita* GDP lower than the threshold in 2012, they go out in the second commitment period.
- Flatrate, Jacoby and Multicriteria, providing only quota reduction rates, require some reference to define the first quota. For Parties joining in 2013 and having participated in Kyoto at the previous period, we select their Kyoto quota as reference. For regions not participating in Kyoto during the first commitment period (such as USA) or joining later, the reference is the business-as-usual emission level of the region in the previous period, which thus depends on the scenario.

To compare the distributive impacts of these five rules, we calibrate them so that they result in the same total cumulated emissions over period 2008-2052 under the median IIASA-WEC A1 scenario. Although the time distribution of emissions matters, cumulative emissions are a good first-order proxy for the impact of each rule on climate change. We use a reference 350 GtC budget, which corresponds to the road towards stabilization of atmospheric CO_2 concentrations at 550 ppm in 2100 under a median scenario in between the WGE and WG1 paths[12].

We will see in the next section that *ex post* cumulative emissions may differ from that target depending on the scenario effectively realized. By choosing a median scenario, we allow for overshooting. Some constituents may argue that the worst scenario should be used to make sure the emission target is reached.

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[12] WRE and WG1 are two sets of world emission trajectories leading to the same atmospheric CO_2 concentration in 2100. WRE is characterized by higher emission levels at first, but by a sharpest decrease afterwards (Houghton *et al.*, 1997).

This debate, which ultimately boils down to Parties' beliefs about the damages of climate change (Ambrosi *et al.*, 2002), is beyond the scope of the present paper. Our choice here is not normative, but simply reflects what we think Parties might realistically agree on.

Table 5 below summarizes the parameters we selected for each rule. We detail below how these figures were obtained.

Rule	Parameter	Value
Flatrate	Quota reduction rate from one period to next	-1 %
	Per capita GDP threshold	US$3000
Per capita allocation	*Per Capita* emission quota	900 kgC/yr
Contraction & Convergence	World Emissions Envelope	Mid
	Convergence year	2030
	α	4
Jacoby	*Per capita* GDP threshold (GDP^*)	US$3000
	α	0.01
	β	0.3
	γ	0.01
Multicriteria (Norwegian)	*Per capita* GDP threshold	US$3000
	a	0.001
	b	0.001
	c	0.001

Table 5: Parametrization of each rule to reach either cumulative emissions of 350 GtC over period 2008-2052 under the IIASA-WEC A1 scenario.

For Flatrate, there is a trade-off between the rate at which the quotas diminish and the value of the *per capita* GDP threshold. The higher the threshold, the tighter carbon constraint has to be on OECD Parties. For example, a threshold of $10,000 (no developing region enters before 2050) would require a –7.5% decrease of Annex B quotas from one period to the next, a $4,000 quota would still require -2.5%, while $1,000 would allow quota to rise by 2% from one period to next. We choose here a $3,000 value, which requires slightly decreasing quota (-1%)[13].

We use the same threshold in the Jacoby scheme, but in that case there is still some flexibility as one can play between the initial emission growth countries are entitled to when they cross the GDP threshold (parameter γ), and the speed with which this initial rate decreases as *per capita* GDP increases. We use here the set of parameters suggested in Jacoby *et al.* (1999). Under these assumptions, Parties can still increase their emissions by 1% per period when they join. The turnout point occurs when they are 30% richer, i.e. at $4,000/cap GDP. From this point onward, their quota must diminish from one period to the next, at a rate which reaches 1% for a per capita GDP of $13,000.

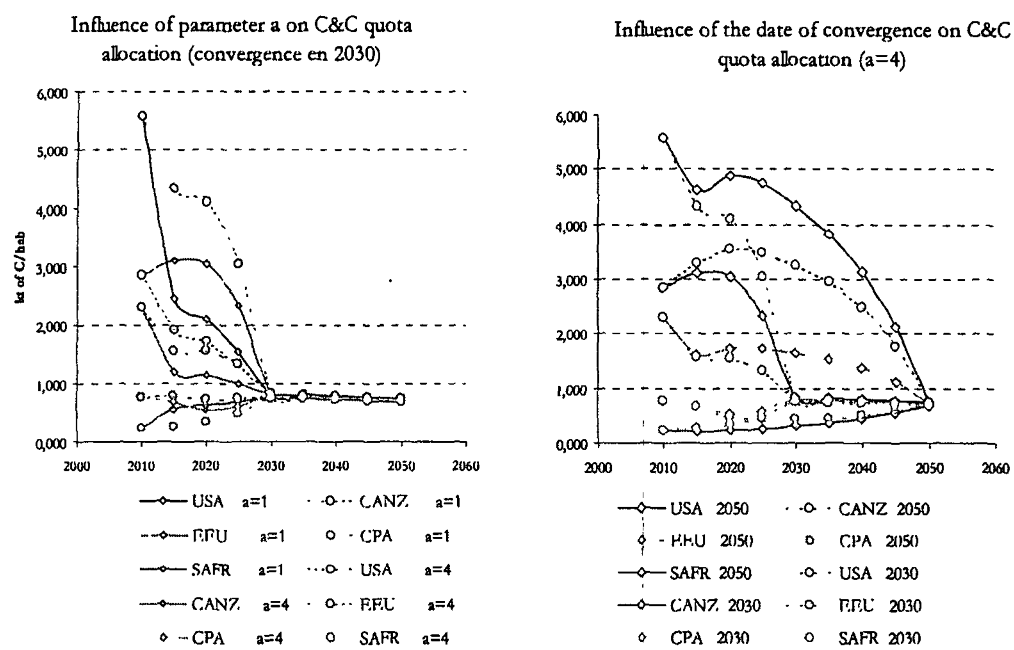
In the Multicriteria proposal, we choose to attribute equal weights to the three (normalized) parameters. Simulations with a 0.5 weight attached to one of the parameter, and 0.25 to the other two led to no significant deviations in terms of quota allocation along the reference scenario. We scale these parameters

[13] Although it may look small, this value actually requires a rather strong effort given the fact that during the first commitment periods, world emissions in the baseline rise by 6 to7% from period to the next in the IA1 scenarios. In other words, the total effort is actually –7 to 8% (worldwide, regional levels may vary).

at 0.001. In other words, for the average country within the group with quotas, the rate at which quota must decrease from one period to the next is 0.3% This is a rather low figure, but it is sufficient given that there are large emitters way above the average.

For the *per capita* allocation, the individual emission quota derives immediately from the cumulative emissions target. We find a *per capita* quota of 0.9tC/hab/year. This is lower than current world average (1.06). China, India and most low-income countries are below. Most middle-income countries, and oil exporters, are above.

Last, for contraction and convergence, the global volume of emissions and burden sharing are entirely disjoint, and we are free to use any sharing parameter. We conservatively select the values made in the original proposal by the Global Commons Institute, i.e. a convergence date of 2030 and a convergence speed parameter $\alpha = 4$. Figure 4 and 5 below show that the sensitivity of quota allocation to these parameters is high.



Figures 4 and 5: Influence of parameters a and convergence date on quota allocation.

6. Effective emissions: how baselines matter

We are now armed to analyze the economic consequences of adopting various quota allocation rules in 2013 under the different baseline scenarios described in 4.1, using the model developed in section 3. The model is programmed under GAMS. The code of the program is available from the authors upon request. The next three sections aim at discussing our results.

In this section, we analyze how each of the selected rules effectively performs in terms of total cumulated emissions, taken as a proxy for environmental performance. Despite the fact that they have all been calibrated on a 350 GtC target for the medium scenario IIASA-A1, figure 6 demonstrates that total emissions over the nine commitment periods vary significantly depending on the baseline scenario. The range of variation, however, depends on the selected rule.

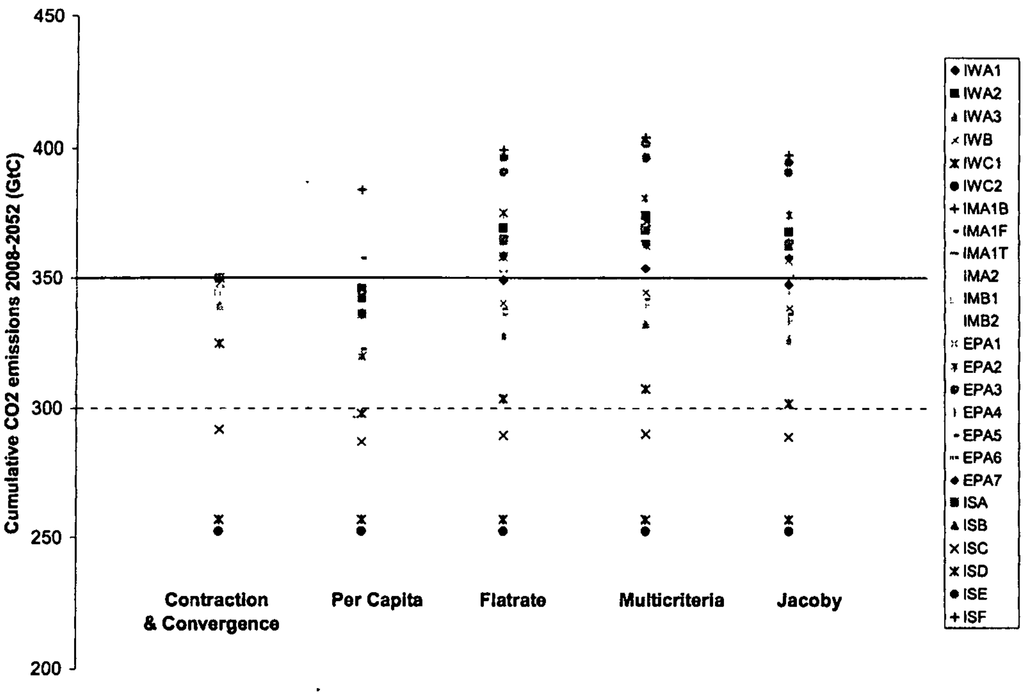


Figure 6. Cumulative emissions (2008-2052) for each quota allocation rules

6.1. Contraction and Convergence and Per Capita

Contraction and convergence is the only rule, which effectively caps emissions at the agreed target[14]. Downward deviations occur only if, at some point in time, baseline emissions are lower than the predefined envelope. However, it is not because aggregate baseline emissions are below the envelope that regional baseline emissions are below the quota allocated under the contraction and convergence rule. In fact, even in the lowest point of the contraction and convergence column (scenario IC2), OECD regions still experience substantial deficit of allowances.

Under the per capita rule, the key driver of cumulative emissions is population growth. Scenarios with higher population growth rate overshoot the target (e.g. IS92f), while scenarios with lower population rate

[14] We have normalized cumulative emissions so that differences in US and non-Annex B emissions during the first commitment period (2008-2012) do not appear. Indeed, since the rule applies only to 2013 onward, these variations are not a consequence of the adoption of the selected rule. In any case, the volumes are very low (below 10GtC).

result in better environmental performance. In the latter case, and contrary to the preceding rule, the global emission constraint is more stringent. The price of carbon may not be higher though since baseline emissions may still be below the computed world quota, for example in the case of the lower three scenarios (IC1, IC2 and IS92c).

If we exclude these three scenarios, the range of cumulative emissions is still large: from 298 to 384 GtC, that is a 25% variation around the 350 GtC target. This result, however, is strongly dependent on the two extreme population growth assumptions (+0.51% in IS92d and +1.34% in IS92f). Leaving them aside, the range is narrowed to 320-367 GtC, or 13% around target. This is a reasonable figure compared to the uncertainties surrounding the measurement of non fossil fuel CO_2 and non-CO_2 emissions.

6.2. Flatrate, Jacoby and Multicriteria

In the flatrate rule, two effects impact on total cumulated emissions. First, because of the \$3,000 *per capita* GDP threshold, the time at which regions take their first commitment depends on the baseline scenario. Figure 7 below shows how. If all OECD countries join in 2013, Former Soviet Union actually go out of the coordination and do not come back until at least 2018. Within developing countries, Latin America and Middle East (MENA) enter rapidly, while the three Asia regions (CAP, SAS and ROA) do not enter before 2018 at best. Sub-Saharan Africa remains out of the coordination in most of the scenarios.

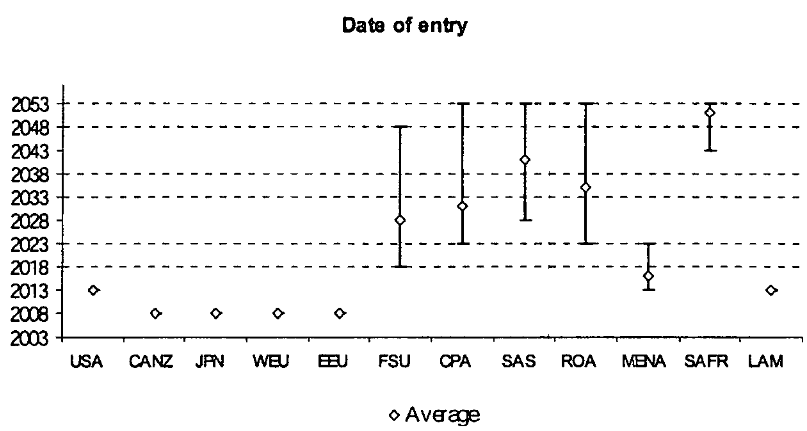
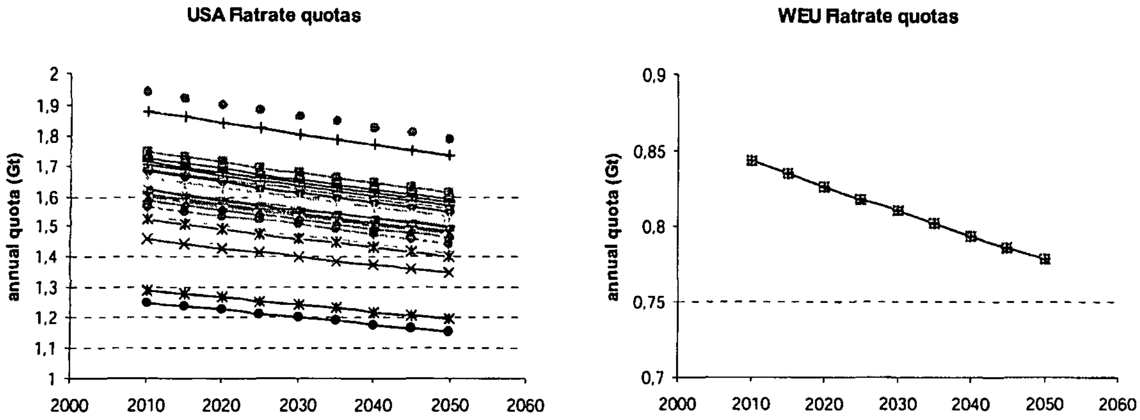


Figure 7: Range of dates at which regions take on first commitments (flatrate rule, threshold \$3,000 per capita).

Second, since we assume that the first quota for Parties joining the coordination is based on its previous period business as usual emissions, baseline scenario has a very strong influence on the initial quota and on the total cumulative quota (since the rate of variation from one period to the next is fixed). The example of the USA is striking. This region enters in 2013 in all scenarios, but with an initial quota ranging from 1.25 to 1.94 GtC/year depending on baseline emissions in 2008-2012. The total emissions the region is allowed to during period 2013-1052 vary accordingly from 10.8 to 16.7 GtC. WEU represents the polar case where the initial quota is fixed regardless of the baseline scenario because of the Kyoto reference (Figure 8).



Figures 8: Quota allocation for USA and WEU regions under Flatrate Rule.

Overall, total emissions under the flatrate rule range from 304 to 399 GtC, a 24% range around the 350 GtC target (again excluding IC1, IC2 and IS92c). But this time, the results are more evenly spread and do not depend only on a few extreme scenarios, as illustrated by a much higher standard deviation than in the per capita case (35 against 28).

The same two effects are at play in the Jacoby and Multicriteria rules. But there, contrary to the flatrate case, the evolution of the quota between periods also depends on observable parameters: *per capita* GDP (Jacoby) and *per capita* GDP, *per capita* emissions and carbon intensity of value added (Multicriteria). In both rules, the higher these parameters, the faster the quota diminishes. Our numeric analysis, however, shows that these variations are negligible compared to the initial difference in quotas. For example, in the USA case, which is the most extreme because all three parameters are high, cumulative quota from 2013 to 2052 range from 10.8 to 16.7 with the Flatrate rule, against 10.4 to 15.9 with Jacoby and 11.0 to 16.9 with Multicriteria. In other words, the rule does not correct the initial differences in emissions due to the baseline scenario.

The three rules, in fact, have slightly different behavior. Since *per capita* GDP enters into the computation of the rate, Jacoby tends to be stricter for developed countries, and slightly more lenient for developing countries. The figures for the USA illustrate that point. Second, the Jacoby scheme is devised so as to leave room for emission growth after regions have joined in (parameter γ), while Multicriteria and Flatrate force quotas to decrease from the start. The resulting effort is always comparable, but for countries with low or intermediate *per capita* GDP, Jacoby creates a smoother transition. Developing nations and Economies in transition beneficiate, at least in the short and medium term.

Multicriteria, on the other hand, can only generate decreasing quotas. As Jacoby, it tends to be more constraining on high emitting, rich and carbon intensive countries. For OECD countries, the rate at which their quota diminish under that rule increases over time as developing regions come in and push down the averages for the three parameters under consideration.

But at least relative to Contraction and Convergence and *per capita*, Jacoby, Multicriteria and Flatrate are quasi-identical. In other words, what matters for the negotiation is not which rule is selected, but the date at which developing countries join the coordination. This shows the critical importance of the rules governing entry and initial quota, a point that is often overlooked when the schemes are discussed *in abstracto*.

6.3. Regional quota allowances

Regarding regional allowance of quota, the only additional point we need to make is that under Per Capita and Contraction and Convergence, developing countries are awarded excess allowances compared to their baseline. As Figure 9 demonstrates, this occurs immediately under a *per capita* allocation, and later on in the contraction and convergence case. In both cases, the volumes of "tropical *hot air*" can be very significant, up to 2 GtC on average or 25% of the World's total allowed emissions under these rules[15].

It is important to note that tropical hot air is not reserved to scenarios where the overall baseline is already very low such as IC1 or IC2. On the contrary, it stems from the very structure of the Per Capita and Contraction and Convergence rules, and thus appears in all scenarios. In fact, it would require a very low *per capita* allowance level (basically below current *per capita* emissions level in developing countries), to make tropical hot air disappear. It thus constitutes a significant part of the rent for developing nations, but also a significant added burden to developed ones.

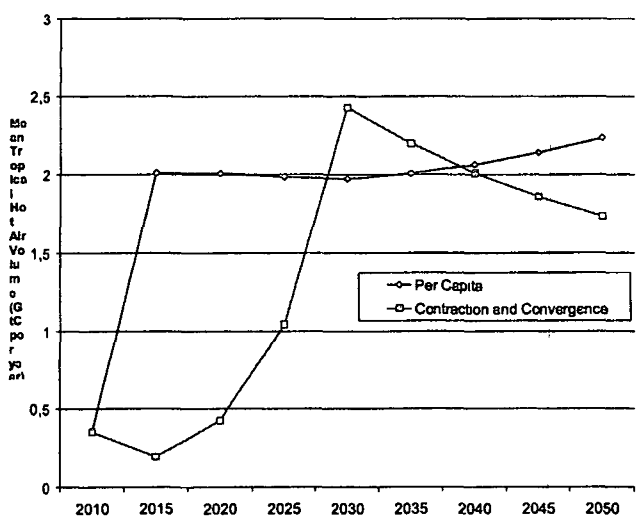


Figure 9: Annual volume of "tropical hot air" distributed in the IA1 scenario, under per capita and Contraction and Convergence rules.

[15] Potential "hot air" in Russia and Economies in transition for the first commitment period is estimated between 422 and 600 MtC per year (UNFCCC, 2001)

7. Price of allowances

We now turn on to the economical consequences of each rule, starting with the price of allowances. Figure 10 shows the evolution of the international price of allowances over time in the Jacoby (taken as representative of Multicriteria and Flatrate), Per Capita and Contraction and Convergence cases.

Let us first look at the Kyoto period. If we exclude the top three points, which assume very high (and probably unlikely) emission growth rates in Europe and Japan from now on to 2010 (scenarios IS92a, e and f), the price of allowances (also called price of carbon) in the first commitment period ranges from $0 to $68/tC[16]. These values – which stem from the uncertainty on baselines and do not incorporate uncertainty on abatement costs – are consistent with the range of projections in the literature (see e.g. Jotzo and Michaelowa, 2002 and Den Elzen and de Moor, 2002) and on line with the findings of a survey of expectations by main market players for prices around $40/tC (Natsource, 2002)[17]. This result, however, only provides comfort in the internal consistency of our model, but does not constitute an independent validation since the EPPA curves are used in the referenced studies.

Beyond 2012, market dynamics are widely different depending on the rule. In the contraction and convergence case, prices rise quasi linearly from one commitment period to the next, reaching $0-$95 in the second commitment period (average $52), $0-$180 ($76) in the fourth and $0-$360 ($165) in 2048-2052. This trajectory reflects the shape of the global emission envelope, in which emissions are first allowed to rise and then decreases after 2020, thus tightening the constraint only progressively with regard to the baseline.

Under the *per capita* rule, prices are already very high in the second commitment ($0-$162, av.$102 in the second commitment period), but they grow only lightly from then on to the ninth commitment period (range $0-$358, average $122 in 2050). The reason is that *per capita* does not incorporate a transitional period.

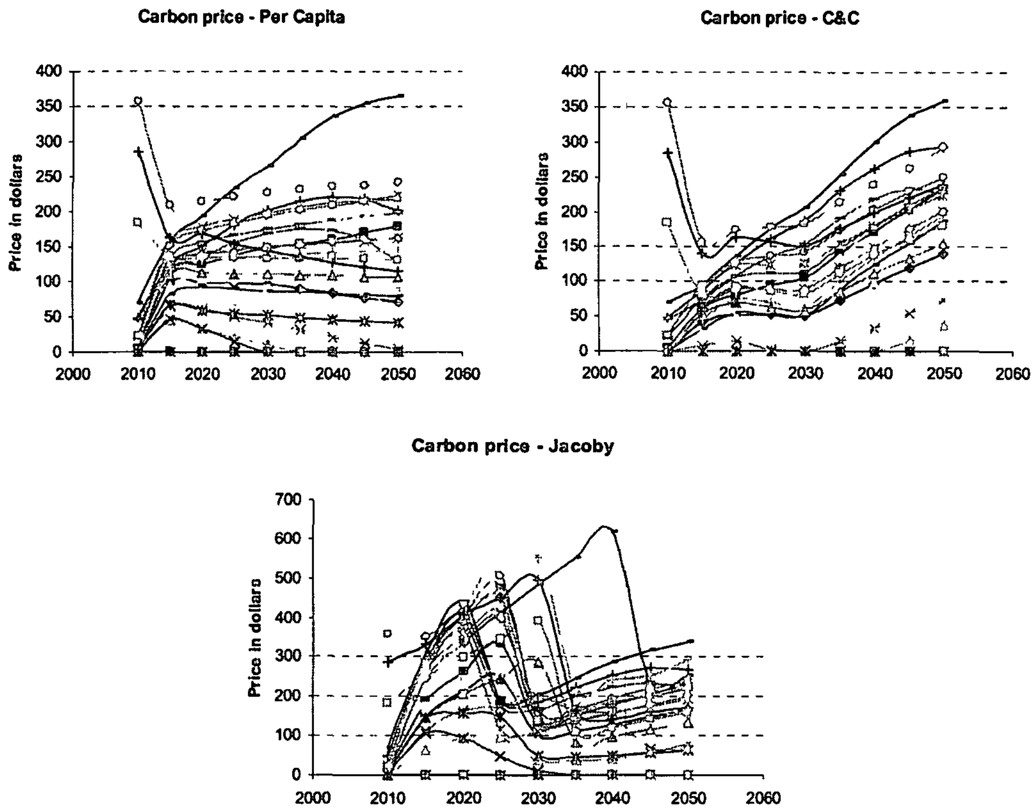
Price trajectories in the Jacoby case are very different. In most scenarios, prices present huge spikes (up to $350 for the most pessimistic scenario) and then decrease sharply. The reason is that the composition of the market changes over time. As economies in transition and developing countries join, a new supply of low-cost abatement potential becomes available. For CPA and SAS, this effect is large enough to more than offset the additional costs induced by the tightening target: as a result, the price drops.

In reality, several factors might concur to mitigate price spikes. First, should a mechanism similar to the CDM be introduced, regions will be able to tap at least part of the low cost abatement potential in regions without quotas, thus lowering the price. However, as we have mentioned above, to which extent project-based mechanisms can provide large supply is unclear. Second, banking would allow forward-looking decision makers to prepare for the constraint. At the extreme, perfect intertemporal exchange of allowances coupled with perfect foresight by all players would result in a price rising at the rate of

[16] The price is zero when the excess supply of allowances by EEU and FSU (the so-called "hot air") exceeds the combined demand from WEU, JPN and CANZ. Although this is the correct price of the global constraint, it does not necessarily reflect the effective price that sellers will ask for. In particular, monopostic behavior are not taken into account in our model.

[17] Allowances on the UK market currently trade around $60/tC, but the market is limited. Project-based emission reductions trade between $1 and $25 per tC (Lecocq and Capoor, 2002).

discount regardless of the initial distribution[18]. Third, preliminary results with an alternative model where long-term impacts of abatement are taken into account confirm that price spikes would be greatly mitigated.



Figures 10: Allowance price for the Per Capita, Contraction and Convergence and Jacoby rules.

However, these price spikes still reveal a key constraint of all the schemes in which not all regions participate in the allowance market from the start: tensions are likely to arise when the market does not enlarge rapidly enough. This suggests in turn that OECD countries have an interest in bringing developing countries in, and that some win-win opportunities can be found (at least assuming that developed countries are willing to act). We come back to this point below.

Last, we see that for all the rules, uncertainty on prices is very high. Table 6 summarizes this information for two periods, 2015 and 2050. For each period, two values are provided: horizontally, the price range translates the impact of the choice of rule on the price. Vertically, the price range translates the impact of the scenario on the formation of the price.

[18] However, unrestricted banking would also allow Parties to delay effort indefinitely. The above argument is thus only valid with perfect compliance. The economics of banking without that assumption is beyond the scope of the present paper.

For 2015, the largest uncertainty is observed for the Jacoby rule. Presence / absence of key player in the market combined with initial quota explain why this rule comes first. The impact of scenario on prices for contraction and convergence and for Per Capita is lower, but still significant (about $150). The impact of the rule at a given scenario is very variable, but in the same order of magnitude.

In 2050 on the other hand, uncertainty stems almost entirely from the scenario, and very little from the nature of the rule. Apart from the A2 case, which is special because South Asia (SAS) has not entered in the market by 2050, thus inflating the price, all other scenarios show ranges below $100. Vertically on the other hand, ranges of prices reach at least three times that value. In other words, for the ninth commitment period, and for a given environmental objective, the uncertainty on prices stems almost entirely from the scenario, and not so much from the quota allocation rule, at least within the set we selected here.

Scenario	Allowance Price in 2015 (2000$)						Allowance Price in 2050 (2000$)					
	Jacoby	C&C	Per Cap	*min*	*max*	*range*	Jacoby	C&C	Per Cap	*min*	*max*	*range*
IA1	151	41	97	*41*	*151*	*109*	168	141	71	*71*	*168*	*97*
IA2	187	63	118	*63*	*187*	*124*	233	233	178	*178*	*233*	*55*
IA3	65	0	43	*0*	*65*	*65*	70	37	0	*0*	*70*	*70*
IB	112	8	65	*8*	*112*	*104*	77	74	4	*4*	*77*	*73*
IS98A1B	290	85	125	*85*	*290*	*205*	268	294	201	*201*	*294*	*93*
IS98A1F	311	93	159	*93*	*311*	*217*	338	358	364	*338*	*364*	*26*
IS98A1T	279	73	115	*73*	*279*	*206*	223	227	129	*129*	*227*	*98*
IS98A2	247	25	72	*25*	*247*	*221*	612	251	138	*138*	*612*	*474*
IS98B1	174	0	58	*0*	*174*	*174*	154	82	89	*82*	*154*	*72*
IS98B2	156	29	93	*29*	*156*	*128*	96	89	59	*59*	*96*	*37*
EPA1	259	62	123	*62*	*259*	*197*	228	201	162	*162*	*228*	*66*
EPA2	263	94	159	*94*	*263*	*168*	195	223	222	*195*	*223*	*28*
EPA3	274	95	150	*95*	*274*	*180*	201	249	219	*201*	*249*	*48*
EPA4	287	47	114	*47*	*287*	*240*	294	194	146	*146*	*294*	*148*
EPA5	246	32	82	*32*	*246*	*214*	253	186	80	*80*	*253*	*173*
EPA6	291	76	136	*76*	*291*	*215*	223	234	198	*198*	*234*	*36*
EPA7	244	61	121	*61*	*244*	*184*	220	200	162	*162*	*220*	*58*
IS92A	255	81	136	*81*	*255*	*174*	158	181	132	*132*	*181*	*49*
IS92B	145	55	110	*55*	*145*	*90*	133	154	106	*106*	*154*	*49*
IS92C	104	0	46	*0*	*104*	*104*				*0*	*0*	*0*
IS92D	145	0	67	*0*	*145*	*145*	65	0	41	*0*	*65*	*65*
IS92E	351	158	208	*158*	*351*	*193*	238	293	241	*238*	*293*	*55*
IS92F	331	141	162	*141*	*331*	*191*	171	238	114	*114*	*238*	*124*
min	*65*	*0*	*43*				*65*	*0*	*0*			
max	*351*	*158*	*208*				*612*	*358*	*364*			
range	*286*	*158*	*165*				*548*	*358*	*364*			

Table 6: Minimum, maximum and average equilibrium price of allowances for Jacoby, Contraction and Convergence and Per Capita in 2015 (left) and 2050 (right).

8. Net costs and benefits of climate policies

Figure 11 presents the net annual costs of the climate policy (domestic abatement expenditures plus net costs of trading on the international carbon market) for each region and each of the above three rules (Flatrate, Contraction and convergence and Per capita).

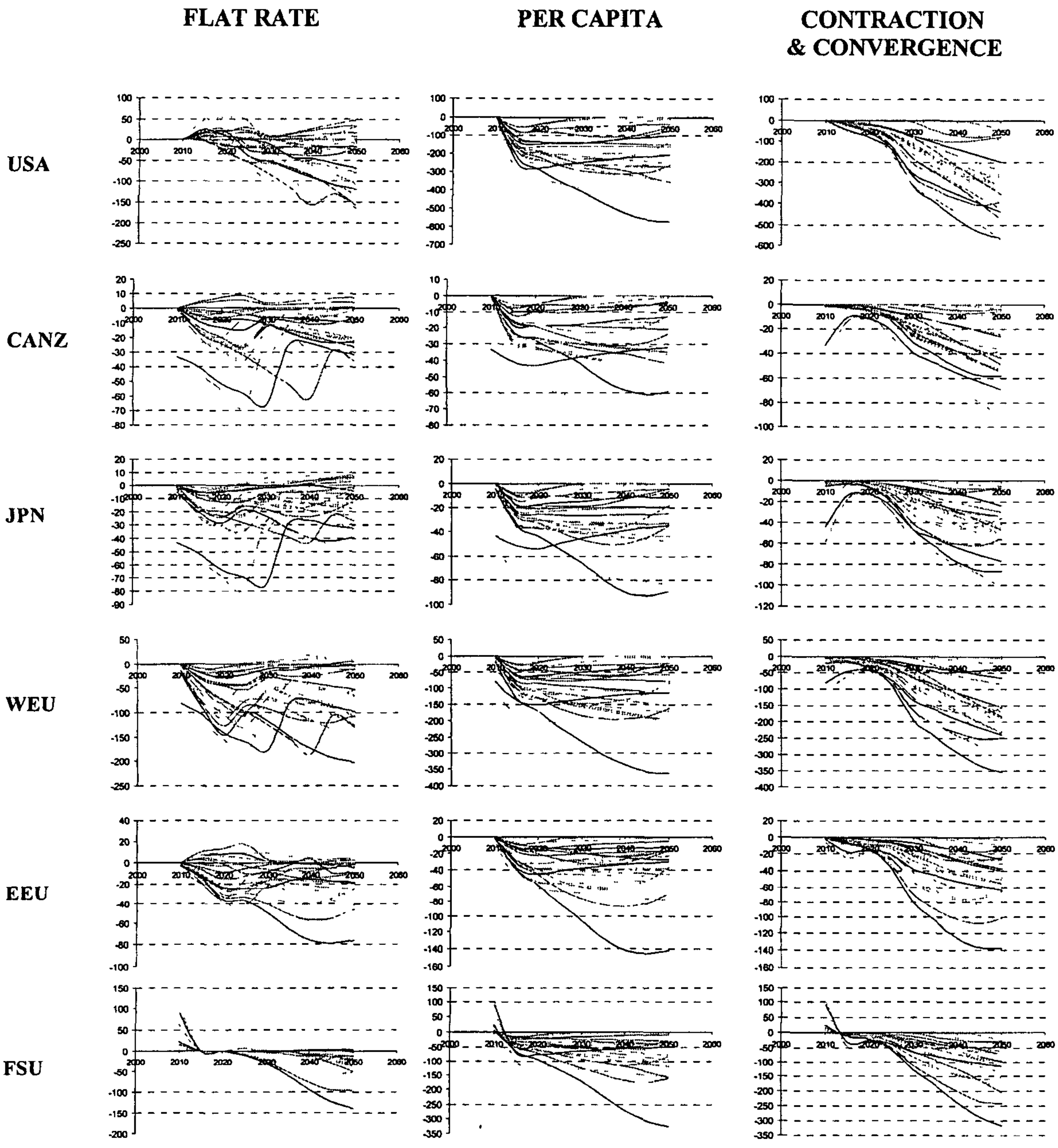
8.1. Regional costs and benefits

Let us first read the figure vertically. For Per Capita allocation, the results follow intuition. Tight quotas for OECD countries, wide discrepancies between abatement costs in the developed and developing world and large volumes of "tropical hot air" lead to large-scale purchases of allowances from the North, and large scale money transfers in return.

Contraction and convergence leads to similar costs and benefits. However, as noted above, the constraint is lower during the first commitment periods. Hence lower net costs and lower net benefits compared to *per capita* in most regions.

For Flatrate, the results are slightly more complex to interpret because the number of regions within the market changes over time, depending on the baseline scenario. In almost all cases, Japan and Western Europe end up with high bills because their constraint is tight and their domestic abatement too high. In general, Eastern Europe and the CANZ region also end up losing money, although they usually sell permits: their total domestic abatement costs are still higher than the revenue they get from selling the permits. It is only in the scenarios where developing countries enter very faraway in the future that they get to sell the most at the highest price, and thus make a profit. The same logic applies to the USA, which has the additional advantage of having its base emissions dependent on its baseline for 2010. The region thus ends up net seller in most scenarios during the first commitment period, and high prices of carbon ensures it makes an overall profit. Former Soviet Union, to a lesser degree, follows the same path.

In the developing world, Centrally Planned Asia is the only net beneficiary, because it enters relatively early in the market and can therefore act as seller of low-cost emission reductions. Sub-Saharan Africa basically never participates, and Latin America, is either net winner or loser, depending on the price of carbon. South Asia, surprisingly, stands to lose much in some scenarios. The reason is that this region is often assumed to experience a very fast economic and emissions growth period starting on or around 2020. However, in some scenarios, it crosses the *per capita* GDP threshold at the beginning of that growth period, and has thus to reduce its emissions by a large volume, resulting in net costs to its economy.



Figures 11: Net costs of the climate policy for three rules (from the left to the right, FlatRate, Per Capita and Contraction and Convergence), all regions and all scenarios.

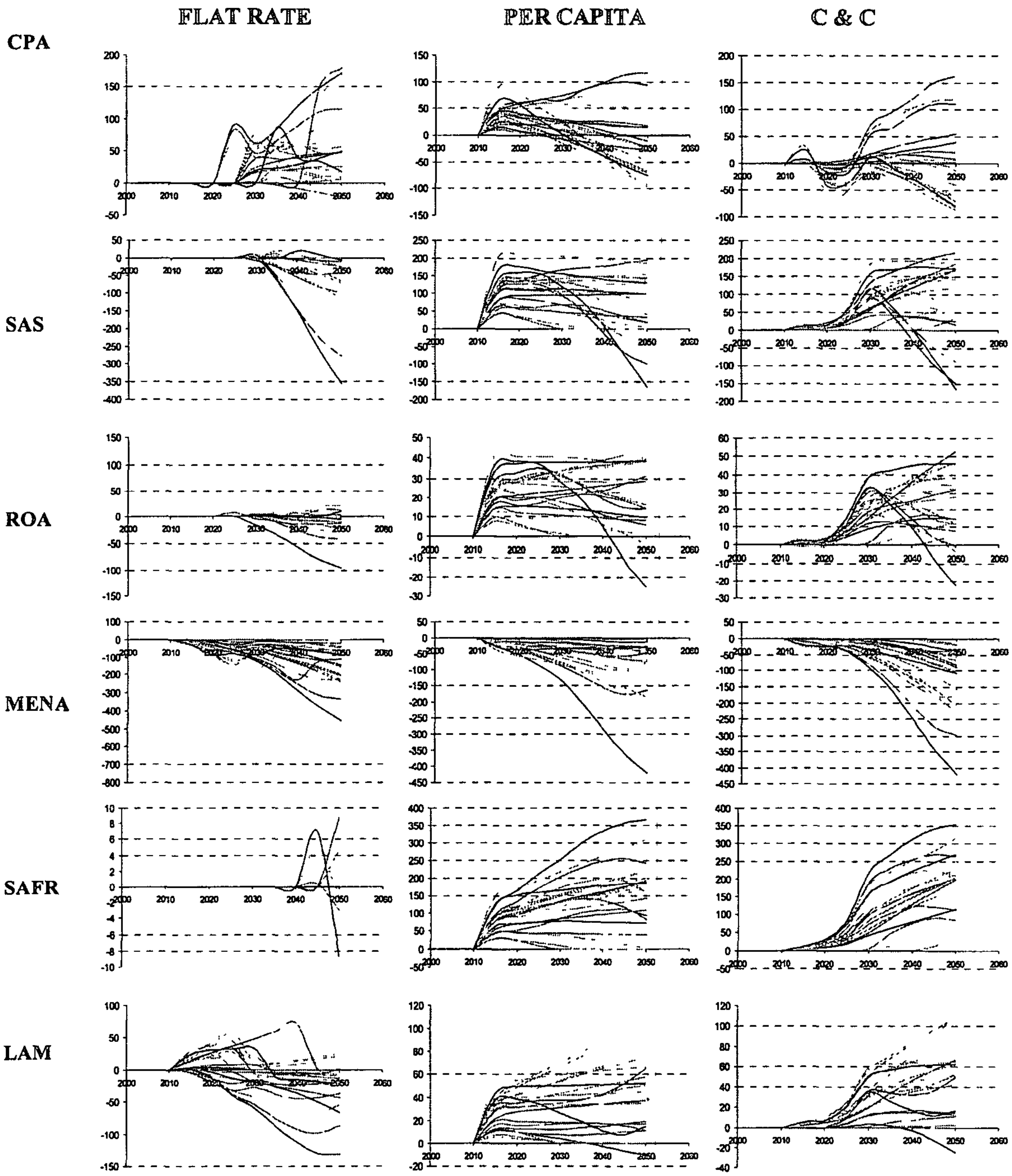


Figure 11 (cont.): Net costs of the climate policy for three rules (from the left to the right, FlatRate, Per Capita and Contraction and Convergence), all regions and all scenarios.

Table 7 presents the range of annual net transfers from OECD to developing countries as a result of purchases of allowances (in b$ per year) in Flatrate, Per Capita and Contraction and Convergence.

	Flatrate		Per capita		C&C	
	2015	2040	2015	2040	2015	2040
CPA	0 to 0	-0,5 to +477	0 to +226	-10 to +453	0 to +111	0 to +449
SAS	0 to 0	-8 to +191	0 to +252	0 to +483	0 to +43	0 to +385
ROA	0 to 0	-7 to +28	0 to +55	0 to +80	0 to +11	0 to +70
MENA	-17 to 0	-358 to 0	0 to +1,5	-255 to 0	-22 to 0	-226 to 0
SAFR	0 to 0	0 to 0	0 to +158	0 to +361	0 to +17	0 to +333
LAM	0 to +65	-56 to +172	0 to +64	0 to +98	0 to +13	0 to +91

Table 7: Annual transfer range to developing countries (billions of US$) for three rules.

In most cases, transfers in the median scenario are far below the maximum depicted here. Still, these figures are very large compared to current flows of ODA and Foreign Direct Investment. And even if prices were divided by 10 (a ratio projection to realized consistent with the SO_2 case, Joskow *et al.*, 1998) the figures would still be considerable, and would raise evident political acceptability issues. But they also lead to questioning the validity of the underlying abatement costs curves in the first place. Can we assume that there is such a gap in abatement costs between the developed world and developing countries, especially in the long run, that would justify such transfers?

The cases of China and India are particularly interesting. EPPA, as all the model we are aware of, assume that costs are very low in these regions which would consequently benefit from huge transfers to these regions. Some elements suggest that there is indeed vast low-cost abatement potential. For example, IEA (2001, p.107) forecasts that China will require about $600b of investment in power generation alone over the next 20 years to meet its demand. Similarly, half of the lodging in 2015 is yet to be built (World Bank, 2002 p.179). But what happens in the other sectors, and what happens beyond the 2000-2020 period is unclear.

8.2. Preferences among rules

Reading Figure 11 horizontally shows for each Party what is the least cost rule without consideration of climate benefits. The complete results with the five rules for both the second commitment period (myopic approach) and the whole 2013-2052 period are presented in Tables 8 and 9 below, but the graphs convey the main messages.

First, for 2015, the pattern is as follows:

- If the cost of carbon is retained as a good cost indicator, the USA strongly prefer a rule with initial quota based on past baseline emissions (Flatrate, Jacoby or Multicriteria) to take profit of its high emissions during the first commitment period. But this in turn illustrates how attractive it might be for non Annex B Parties generally to raise their emissions before they enter the system.
- Other OECD countries see contraction and convergence as the least-cost option. In that case, tighter quotas than in Flatrate, Jacoby or Multicriteria are more than compensated by the possibility

to tap low cost potentials in developing countries because of the presence of all regions in the market from the start.

- Flatrate (or Jacoby or Multicriteria) is the obvious least-cost option for Former Soviet Union, and to a lower degree for Eastern Europe in 2015 because under these rules no action is required at all
- Unsurprisingly, all developing regions (except Middle East and Northern Africa and to a lesser degree Latin America) favor *per capita* allocation, which provides them with the highest net revenue (the price decrease due to tropical hot air is more than compensated by the additional volume of sales they realize). Contraction and convergence is their second choice, suggesting that some convergence of interests with non US OECD.

In short, this description unsurprisingly confirms that North and South have conflicting interests vis-à-vis abatement rules, but it also reveals what might be a very wide gap among Northern nations if the US does not participate in the first commitment period.

Scenario	USA	CANz	JPN	WEU	EEU	FSU	CPA	SAS	ROA	MENA	SAFR	LAM
IA1	MultiCrit	CC	CC	CC	Jacoby	Flatrate	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap
IA2	MultiCrit	CC	CC	CC	Jacoby	Flatrate	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap
IA3	MultiCrit	CC	CC	CC	Jacoby	Flatrate	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap
IB	CC	CC	CC	CC	Jacoby	Flatrate	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap
IC1	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate
IC2	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate
A1B	MultiCrit	MultiCrit	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
A1F	MultiCrit	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
A1T	MultiCrit	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
A2	MultiCrit	MultiCrit	CC	CC	Jacoby	Flatrate	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
B1	Flatrate	Jacoby	CC	CC	Jacoby	Flatrate	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
B2	Flatrate	Jacoby	CC	CC	Jacoby	Flatrate	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
EPA1	MultiCrit	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	Flatrate	Per Cap	Per Cap
EPA2	MultiCrit	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
EPA3	MultiCrit	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
EPA4	MultiCrit	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
EPA5	MultiCrit	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	Flatrate	Per Cap	Per Cap
EPA6	MultiCrit	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
EPA7	MultiCrit	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	Flatrate	Per Cap	Per Cap
IS92a	MultiCrit	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	Flatrate	Per Cap	Per Cap
IS92b	MultiCrit	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	Flatrate	Per Cap	Per Cap
IS92c	Flatrate	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	Flatrate	Per Cap	Per Cap
IS92d	Flatrate	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
IS92e	Flatrate	CC	CC	CC	Jacoby	Flatrate	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
IS92f	MultiCrit	CC	CC	CC	Jacoby	Flatrate	Per Cap	Per Cap	Per Cap	Flatrate	Per Cap	Per Cap

Table 8: Least-cost option for Parties in 2015.

	USA	CANz	JPN	WEU	EEU	FSU	CPA	SAS	ROA	MENA	SAFR	LAM
IWA1	MultiCrit	CC	MultiCrit	MultiCrit	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap
IWA2	MultiCrit	MultiCrit	MultiCrit	MultiCrit	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap
IWA3	Flatrate	CC	Flatrate	Flatrate	Jacoby	MultiCrit	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap
IWB	MultiCrit	CC	MultiCrit	MultiCrit	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap
IWC1	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate
IWC2	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate	Flatrate
IMA1B	MultiCrit	MultiCrit	MultiCrit	MultiCrit	MultiCrit	Jacoby	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap
IMA1F	MultiCrit	MultiCrit	MultiCrit	MultiCrit	MultiCrit	Jacoby	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
IMA1T	MultiCrit	MultiCrit	MultiCrit	MultiCrit	MultiCrit	Jacoby	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap
IMA2	MultiCrit	MultiCrit	CC	CC	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap
IMB1	Flatrate	MultiCrit	MultiCrit	CC	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
IMB2	Flatrate	MultiCrit	MultiCrit	MultiCrit	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
EPA1	MultiCrit	CC	CC	CC	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
EPA2	MultiCrit	MultiCrit	MultiCrit	MultiCrit	MultiCrit	Jacoby	Jacoby	Per Cap	Per Cap	CC	Per Cap	Per Cap
EPA3	MultiCrit	MultiCrit	MultiCrit	MultiCrit	Jacoby	Jacoby	Jacoby	Per Cap	Per Cap	CC	Per Cap	Per Cap
EPA4	MultiCrit	CC	CC	CC	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
EPA5	MultiCrit	CC	CC	CC	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Jacoby
EPA6	MultiCrit	CC	CC	CC	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
EPA7	MultiCrit	CC	MultiCrit	CC	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
ISA	MultiCrit	CC	CC	CC	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
ISB	MultiCrit	MultiCrit	MultiCrit	MultiCrit	CC	Jacoby	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
ISC	Flatrate	CC	CC	CC	CC	Flatrate	Per Cap	Per Cap	Per Cap	Jacoby	Per Cap	Per Cap
ISD	Flatrate	CC	CC	CC	CC	Jacoby	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
ISE	MultiCrit	CC	CC	MultiCrit	MultiCrit	Jacoby	Per Cap	Per Cap	Per Cap	CC	Per Cap	Per Cap
ISF	MultiCrit	CC	CC	CC	Jacoby	Jacoby	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap	Per Cap

Table 9: Least cost option for Parties over 2008-2052 period.

When considering the whole 2013-2052 period, choices are rather different, as shown in Table 9 below, where the rule with lowest total discounted costs over the whole time horizon are reported[19]. The most important variation concerns non US OECD, which is now uncertain between contraction and convergence and multicriteria. The reason is that for those regions, in the long run, the benefits from trade do not offset the costs of more stringent requirements any longer.

Let us conclude by looking at each column in Tables 8 and 9 vertically: for most regions, the ranking of rules remains largely constant across scenarios, especially when considering that Flatrate, Multicriteria and Jacoby are essentially identical. The only exceptions are the Middle East and North Africa region in the first table, which is a very particular case because of relatively high GDP level and very high emissions level, and non-US OECD regions at second period, where the preference between contraction and contraction and Multicriteria depends on the baseline scenario. This suggests that the it is not so much the choice of quota allocation rule which is impacted by uncertainty on baseline scenarios, but rather the price to pay for accepting any given rule, as we have shown at the end of the preceding section.

[19] The discount rate is considered constant and equal to 5%. We performed some calculations with differentiated rates among regions, according to very different rates of growth, but it did not provide significant differences in these results.

9. Conclusion

In this paper, we have reviewed the main rules proposed in the literature to allocate GHG emission quotas amongst nations beyond 2012 and, using a partial equilibrium model of the allowance market, we have examined the economic consequences of the adoption of five of them under a wide range of plausible baseline scenarios. This analysis highlights four key characteristics of quantity-based coordination under uncertainty, and provides insights on some of the difficulties and opportunities Parties will face in the incoming negotiations on the international climate mitigation regime beyond Kyoto.

First, *four out of the five quota allocation rules we have tested do not completely control quantities*, either because not all Parties take emission commitments in 2013, or because quotas depend on the baseline, or both. The contraction and convergence example demonstrates that this is by no means inevitable, but the price to pay is twofold: all countries need to join in 2013, and the global emissions envelope must be negotiated separately. Otherwise, cumulative emissions over the 2012-2052 period can vary significantly (up to 25%). A small range probably compared to what a price-based instrument would lead to over the same period of time, but large enough to limit the environmental attractiveness of the scheme.

In terms of prices, our analysis confirms the early intuition of Hourcade (1994) that regardless of the quota allocation rule selected, *prices of allowances and net costs of climate mitigation for all Parties are very sensitive to the uncertainty on baseline*, and potentially very large under the highest emissions scenarios. This constitutes a strong barrier against the adoption of any of these schemes. Beyond early entry of developing countries in the market, which mitigates costs, the ranges of variations we obtain (even when all countries join in 2013) suggest that some form of price cap might be necessary to reassure Parties; for example through taxes on excess emissions, as in the current Danish regime or in the "safety valve" proposal by Kopp *et al.* (2000). More research is required to assess how uncertain the environmental outcome would then become.

On the other hand, despite the high impact of uncertainty on prices and costs, *the preferences of Parties among rules appear rather insensitive to uncertainty on the baseline scenario*, at least with the abatement costs and global environmental objective we have selected. In fact, configurations where the least-cost rule depends on Parties expectations about future growth or future emissions emerge very rarely in our simulations. As a result, the risk that Parties make strategic use of uncertainty in the negotiations (Allais, 1953) appear to be low as long as the basic choice between joining the international coordination or not has been made.

Fourth, our analysis demonstrates that *the rules governing the entry of new parties into the coordination are critical*. It will come as no surprise that perverse incentives arise when the first quota depends on future emissions (i.e. beyond 2002); and our contribution here is simply to demonstrate the magnitude of this risk in schemes such as Flatrate, Jacoby or Multicriteria where the initial distribution of quota is not significantly altered over time, hence perpetuating the benefits of high initial emissions. Less intuitive, on the other hand, is the fact that the timing of entry matters so much. The reason is that, because of the wide gap between abatement costs in developed and developing countries embedded in the marginal abatement cost curves we have used, prices and total costs can significantly decrease when developing countries join, even if the global constraint on emissions is tightened at the same time.

The last observation has wide ranging implications. First, it suggests that the current debate on quota allocation rules focuses too much on quota allocation *per se*, and overlooks elements that are may be just as important. For example, based on the sole formula for quota allocation, the Jacoby, Multicriteria and Flatrate rules are usually considered no less distinct than, say, Flatrate and Per Capita. But numerical analysis reveals they are in fact quasi-identical if used with the same *per capita* GDP threshold, at least compared to Per Capita or Contraction and Convergence.

But it also points to a possible win-win compromise between North and South, where early participation in the allowance market, and possibly some hot air for the South would be traded against tighter commitments in the North. The contraction and convergence rule, which is the first choice of Europe and Japan, and the second choice of most developing countries, is an illustration. Of course, our analysis also demonstrates that North-South purchases of allowances would be very significant compared to current foreign direct investment, raising obvious political acceptability issues. But assuming enough willingness to pay for the environment and maybe some form of price cap, developed and developing countries would both be better off.

However, at the heart of this possible compromise is the assumption that abatement costs in the South are significantly lower than in the North, and that this difference will be sustained over time. Although common in climate mitigation policy models, this hypothesis is still based on limited evidence. Priority for future research should thus be to discuss and refine it, and to assess to which extent the above convergence of interests would still emerge if the gap in abatement costs were not as wide or as permanent as expected.

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Appendix: Data harmonization of baseline scenarios

The 25 selected original scenarios are based on different regional patterns, as described in table A1 below:

IIASA WEC 98	IMAGE	EPA 98	IS92
NAM	USA	USA	USA
	CAN		
West Europe	OCDE Europe	OCDE West	OCDE West
East Europe	Eastern Europe	EFSU	EFSU
FSU	Former USSR		
South Asia	South Asia		
CP Asia	East Asia	CP Asia	CP Asia
	South East Asia	South East Asia	South East Asia
OCDE Pacific	Oceania	OCDE Asia	OCDE Pacific
Other Pacific	Japan		
Latin America	Latin America (2 parts)	Latin America	Latin America
Africa	Africa (4 parts)	Africa	Africa
North Africa & Middle East	Middle East	Middle East	Middle East

Table A1: Regional aggregation patterns of the four sources of scenarios

To harmonize regions across scenarios, we use a disaggregation – reaggregation process. Disaggregation of a region R (say North America in the IIASAWEC set) into sub-regions R1 and R2 (USA and Canada) is performed as follows. We look for similar scenarios (in terms of population, GDP and emission trajectories) where R1 and R2 and isolated, and we deduce from this reference the shares of R1 and R2 in total population, GDP and emissions of R. Table A2 summarizes which regions were cut in two pieces.

IIASA WEC 98	
Original	Adapted
North America	USA
	CAN
West Europe	West Europe
Eastern Europe	Eastern Europe
FSU	FSU
CP Asia	CP Asia
South Asia	South Asia
Other Pacific	RO Asia
Pacific OECD	Aus + NZ
	Japan
Middle East + North Africa	Middle East + North Africa
SubSaharian Africa	SubSaharian Africa
Latin America	Latin America

IMAGE	
Original	Adapted
USA	USA
CAN	CAN
OECD Europe	West Europe
Eastern Europe	Eastern Europe
FSU	FSU
East Asia	East Asia
South Asia	South Asia
South East Asia	RO Asia (1)
Oceania	Aus + NZ
	RO Asia (2)
Middle East	Middle East + North Africa
North Africa	
East Africa	SubSaharian Africa
West Africa	
South Africa	
Central America	Latin America
South America	

EPA 98 IS 92	
Original	Adapted
USA	USA
	CAN
OECD West	West Europe
EFSU	Eastern Europe
	FSU
CP Asia	CP Asia
SE Asia	South Asia
	RO Asia
OCDE East	Aus + NZ
	Japan
Middle East	Middle East
	Nafrica
Africa	SubSaharian Africa
Latin America	Latin America

Table A2: Disaggregation process

We must stress that the harmonization is not perfect, and some slight disparities remain.

Turkey is included in Western Europe in scenarios from IIASA-WEC, EPA and IS92, and to region MENA in the IS98-IMAGE scenarios. But differences in regional GDP in 1990 from these different models show that the influence of Turkey is not significant considering the original differences in GDP estimations over the whole region:

The disaggregation of Asia is the most intricate and variable among models: IS98-IMAGE include three zones build on geographical criteria, whereas other models gather centrally planned countries. However, regions East Asia from IMAGE and Centrally planned Asia in other modeling approaches all include China as the major country, differences concern Taiwan, Vietnam, Cambodia. We decided not to modify these defaults, since our modifications would affect slightly the storylines behind the scenarios.

Reference year harmonization.

Since 1990 and 2000 data are inconsistent across the four scenario families we use, we normalized all 2000 population and GDP across all scenarios based on World Bank data, and on 1998 data from the International Energy Agency for fossil CO_2 emissions. We recomputed the scenarios based on these values, and on the original growth rates.

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